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Metamaterials modelling, fabrication and characterisation techniques

Radu Malureanu[1)], Maksim Zalkovskij[1)], Andrei Andryieuski[1)], Andrey Novitsky[1)], Alexandra Ivinskaya[1)], Peter Uhd Jepsen[1)], Aurelian Popescu[2)], Dan Savastru[2)], Christian Kremers[3)], Dmitry Chigrin[3)], Andrei Lavrinenko [1)]

[1)] *Department of Photonics Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark*
[2)] *National Institute for Optoelectronics, INOE 2000, Magurele, Romania*
[3)] *Bergische Universitat Wuppertal, Wuppertal, Germany*

Oersteds plads, bldg. 343, DK-2800, Kgs. Lyngby, Dk; rmal@fotonik.dtu.dk

Summary:
Metamaterials are artificially designed media that show averaged properties not yet encountered in nature. Among such properties, the possibility of obtaining optical magnetism and negative refraction are the ones mainly exploited but epsilon-near-zero and sub-unitary refraction index are also parameters that can be obtained. Such behaviour enables unprecedented applications.
Within this work, we will present various aspects of metamaterials research field that we deal with at our department. From the modelling part, various approaches for determining the value of the refractive index, permittivity and permeability can be used and we will present the ones developed and used at our group. Also, using transformation optics approach, one can determine the needed values for the permittivity and permeability in order to obtain the needed functionality. Approaches in this area will be presented.
From the fabrication point of view, various 2D and 3D high resolution patterning techniques are used. The talk will describe the ones available within our group, starting with the classic UV-lithography and ending with more advanced ones, e.g. 2-photon-polymerisation and electron-beam lithography.
Measuring possibilities, both in the VIS/IR and well as in the THz regime, used for characterising the samples will be presented. The experimental challenges will be tackled during the talk.
Keywords: metamaterials, nano-fabrication, modelling techniques.

Motivation

Nanostructured MMs have demonstrated light traps for thin-film solar cells (plasmon-enhanced solar cells)[1], THz lasing in active metasurfaces based on plasmonic graphene structures[2], enhancement of the irradiative heat transfer in thermo photovoltaic systems[3] and solar troughs[4], protein nanosensing (plasmonic nanowire media for new bulk SERS schemes)[5], UV lasing[6], nanosensing of bacteria by field-enhanced fluorescence (plasmonics metasurfaces)[7], coherent 2nd harmonic generation based on nonlinear bulk MMs[8], etc. Numerous microwave applications of microstructured MMs are summarized in[9]. However, there are several aspects still to be taken into consideration before industrial implementation of such structures. For example, the analysis of electromagnetic properties of MMs and retrieval of their effective macroscopic parameters still face serious difficulties[10], and the progress in their implementation on the level of industrially adapted devices is hindered by the lack of systematic characterisation procedures of new MMs. The most important current issues are the physical meaning and experimental determination of electromagnetic material parameters (EMP). Other parameters are related to sample geometry, chemical composition, thermal conductivity, etc. and can be determined relatively easily using conventional techniques. The situation with the EMP

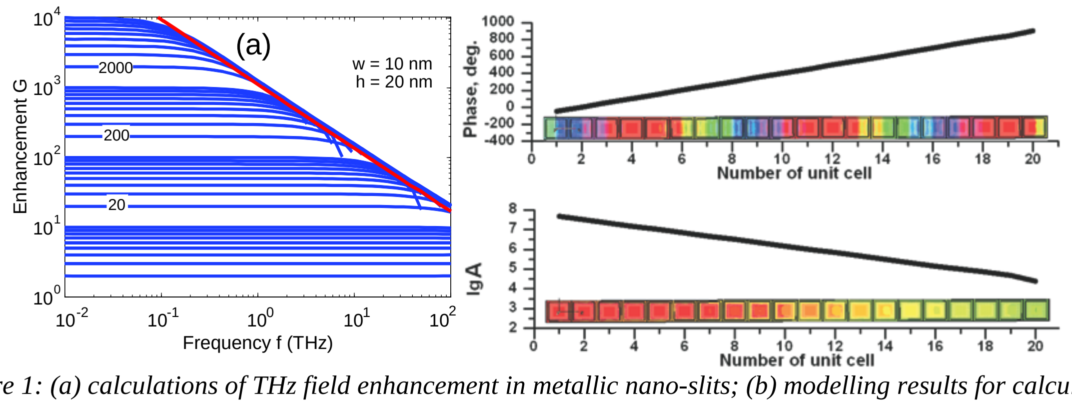

Figure 1: (a) calculations of THz field enhancement in metallic nano-slits; (b) modelling results for calculating the effective refractive index

of MMs is more complicated: if the standard procedures which require a negligible optical distance between adjacent atoms are applied to MMs, they tend to provide inaccurate EMPs which violate the basic constraints imposed by passivity and causality. It has recently also been recognised that tailoring the nano and microstructure may enhance a great diversity of nonlinear effects, though their exploration is still in the nascent state[11].

Results

From the theory/modelling side, we will present both ab-initio activities, among which calculating the enhancement of THz fields in periodic metallic nano-slits (fig. 1(a))[12], developing our own transformation optics approach methodology[13] as well as simulation ones, for example determining the effective refraction index using our own WPRM method (fig 1(b))[14], optimising the geometry of optical nano-antennae[15] etc.

In the fabrication field, our expertise lies in utilising various lithography techniques, from UV lithography to electron-

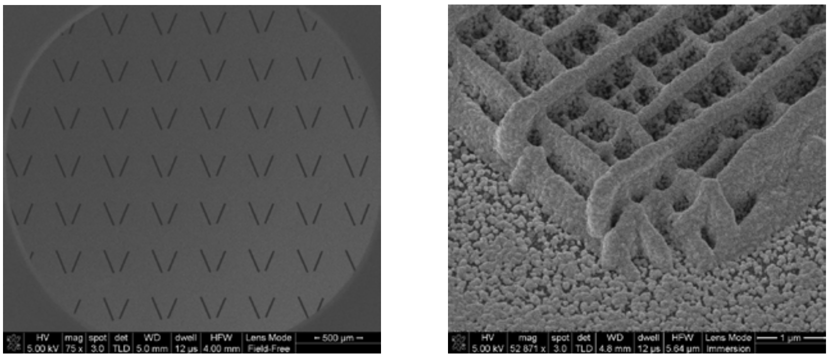

Figure 2: (a) SEM image of V-shaped slits fabricated on metallic membranes and (b) 3D metal-covered dielectric structures fabricated using 2-photon polymerisation and electroless metal deposition

beam and tow-photon polymerisation ones to obtain the desired structures. Also, metal and dielectric etching and deposition are among our strengths. Due to the need for metal deposition on 3D complex structures we developed, based on the Tollens reaction, our own recipe for covering such structures. [16]A detailed account for the fabrication possibilities will be presented during the talk.

The characterisation developed on in two main directions. In the THz regime, several time-domains characterisation setups are available, ranging from 0.1 to 30 THz and with different peak powers. A detailed description of the setups as well as obtained measurement results[17] will be presented. From the optical side, we have the possibility of spectroscopic measurements for broad (500-1700nm) range of normal incidence transmission and reflection amplitudes and we are in the process of expanding the setup towards variable incidence and scattering angles measurements possibilities. Schematics of the system will be presented.

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